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Flame radiation feedback to fuel surface in medium ethanol and heptane pool fires with cross air flow

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ABSTRACT

The work in this paper is to clarify and quantify experimentally the effect of cross air flow on flame radiation feedback to fuel surface in medium pool fires. Square pools with dimensions ranged in 10–25 cm are burnt under cross air flow speed ranged in 0–2.5 m/s, using ethanol and heptane as representative fuel producing flame of definitely different sootiness and luminosity as to compare their response to the cross air flow in radiation feedback. The incident radiation heat flux to the fuel surface is measured by a step-sum method using water-cooled radiation gauges on discrete regions of the surface, along with the fuel mass burning history recorded simultaneously by an electronic balance with resolution of 0.1 g. Results show that the cross air flow, by deflecting the flame, reduces the radiation feedback remarkably to finally approach a nearly stable lower value with increase in flow speed. Such reduction relative to that with no wind is quantified, as found to be more effective for heptane pool fire (50–70%) than that for ethanol pool fire (25–35%). However, at the same time, the burning rate is enhanced by the cross air flow. The two fractions, χ_a (fraction of radiation heat absorbed by fuel surface to that needed for evaporation) and χ_s (fraction of incident feedback radiation to total heat released by combustion), are then further quantified. They both decrease considerably with increase in flow speed. The χ_a and χ_s under no wind are shown to be quite different for heptane (range in 20–60% (χ_a) and 0.5–1.5% (χ_s) increasing with pool size) and ethanol (nearly constant 25% (χ_a) and 2% (χ_s) independent of pool size). However, when subjected to a relative strong wind as Froude number (Fr) beyond 1, χ_a is found to be similar for these two different fuels (in 5–15%), but χ_s found in 0.4–1% for ethanol and in 0.1–0.5% for heptane. The behaviors of pool scale effect on both flame radiation feedback fraction (χ_a), and accordingly mass burning flux, with a cross air flow are shown to be quite different from those without cross air flow. The flame radiation feedback fraction (χ_a) increases with pool size and is much higher for heptane than that of ethanol at no cross air flow; while it is similar for these two fuels under a cross air flow and being much lower than that with no cross air flow. Accordingly, the mass burning flux increases with pool size at no cross air flow; while being similar at a relative higher value regardless of pool size for a given Fr with a cross air flow than that with no cross air flow (pool scale effect showing to be well converged by Fr when subjected to a relative strong cross air flow as Fr beyond the critical value of about 1). These quantifications and findings reveal that under a cross air flow, the relative importance of different heat feedback mechanism of a pool fire has been altered prominently due to the deflection of the flame. Flame radiation feedback declines remarkably while those from wall conduction and flame convection should be enhanced to be predominant, which is essential in re-considering the heat balance to characterize and especially to scale the burning behavior of a pool fire in cross air flows.

1. Introduction

Pool fire behaviors and characteristics have been investigated for decades and still attract extensive attention. Flame height and temperature (e.g., [1–6]), heat transfer balance (e.g., [7–18]), and burning rate (e.g., [2,3,19–25]) of a pool fire have been mainly studied and reported in the literatures. The burning rate of a pool fire is determined by the heat supply feedback from the rim walls or the flame to the fuel in different pool scale regimes [3]. For small pool fires in the laminar flame flow regime, for example less than 0.1 m, the conductive heat supply down through the rim walls is dominant, thus its burning rate (per unit surface area, mass flux) decreases with increase in pool size. Thermal radiation feedback from flame to the fuel surface begins to be more and more important in the transition flame flow regime as pool fire beyond 0.1 m,

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leading to an increment of burning rate mass flux with pool size, and final approaching an asymptotic value for large pool fires in the fully turbulent flame flow regime, where flame radiation feedback is overwhelmingly predominant. So, with the increase in pool size, the dominant heat supply mechanism varies from conduction to convection and finally radiation. In the medium size transitional regime, the dominant heat supply transfers from convection to radiation. With the increase in burning mass flux with pool size, the convection importance declines as the heat is "blowing away" by the convection motion of the evaporated fuel.

As for the flame radiation characteristics, many studies have been reported on the flame radiation emissivity to surroundings of hydrocarbon pool fires. Muñoz [3] investigated the radiative characteristics of large gasoline and diesel pool fires by outdoor experiments. Koseki and Yumoto [7], Jensen et al. [8], Mudan [9], Munoz et al. [11] had investigated the geometric and radiation power of hydrocarbon pool fires. He and Shoji [12] and Nakakuki [13,14] had developed models to calculate the heat transfer in pool fires. Compared to this, studies on radiation feedback to the fuel surface is relatively limited, e.g., [10,15,18]. Hamins et al. [15] had carried out experiments and revealed that local incident radiation feedback to the fuel surface declined radially along the surface. Brosmer and Tien [18] had investigated the radiation blockage effect due to the fuel-rich core region above the fuel surface and at the base of the flame. These works present valuable observations and investigations into the radiation feedback characteristics of pool fires, but mainly in a quiescent ambient air condition, in which the flame is just sitting straightly above the fuel surface.

The studies on pool fire behavior under a cross air flow wind condition are still relatively fewer. With a cross air flow, as the flame is deflected, the heat feedback from the flame and thus the burning behavior of a pool fire will be more complex than that in a quiescent air condition. The current studies on this issue are mostly concerning the effect of cross air flow on the overall outcome of burning rate of a pool fire [20–25] in pursuit of the evolution of burning rate with cross air flow speed. However, basically under-lying physics is that the burning rate is controlled by the heat feedback through different mechanisms including conduction, convection and radiation. The position of this work is to provide an in-depth insight quantification to distinguish how the flame radiation feedback as well as its importance in contribution to the mass burning rate of a pool fire change due to a cross air flow. This provides fundamental base for scaling the pool fire burning behavior in a cross air flow, as different dominant heat feedback mechanism has different scale law. The radiation feedback in a pool fire is determined by the flame shape, size, temperature and emissivity. As the cross air flow will change the flame shape and angle, the radiation feedback should also change significantly. A further concern can then arise accordingly regarding to the behavior of pool scale effect on mass burning flux of the pool fires with a cross air flow, especially for medium pool fires in the transition flame flow regime, where the flame radiation feedback importance increases and the mass burning flux has an increasing trend accordingly with pool scale in the case of no wind. However, still no work or experimental measurement has been reported in quantification of the evolution of flame radiation feedback to fuel surface in pool fires with cross air flow speed. This will be found out as a task undertaken in the present work.

In this paper, experiments are designed and carried out for different medium size square pool fires, taking ethanol and heptane as the representative fuel. The flame radiation feedback to the fuel surface in pool fires is measured and its variation with cross air flow speed is quantified. The effects of cross air flow on the two important fractions, χ_a (fraction of radiation heat absorbed by the fuel surface to that needed for fuel evaporation) and χ_s (fraction of incident feedback radiation to that total released by combustion), as well as accordingly the behavior of pool scale effect on the mass burning flux of pool fires, are then further discussed. There are three more sections following the introduction. The second section describes the experimental facility, measurement setup and conditions. The third section presents the experimental results and analysis followed by the conclusion section summarizing the major findings of this work.

2. Experimental

The overall schematic of the experimental setup is shown in Fig. 1. The horizontal cross air flow is generated by a wind tunnel with mechanical fan installed at one end, providing a screened air flow of 0–4.5 m/s. The total length of the tunnel is 72 m, which assures the flow to be full developed, with a cross section of 1.5 m wide and 1.3 m high. The other end of the tunnel is open. Concerning the relative small size of the cross section which will lead to constraint and re-radiation effect from the tunnel boundary wall to the burning and flame behavior, the pool fire is positioned just outside the opened end and close to the portal to eliminate above complex effects. The upstream cross air flow speed at the portal is monitored by a four-probe hotwire anemometer with typical measured velocity data and time-fluctuations together turbulence statistical values of u_{rms}/u_{mean} (about 5%) also shown in Fig. 1. The distance between the pool fire center to the portal of the tunnel is 0.3 m. Before the experiments, the wind velocity above the pool center is measured, which is convinced to be identical to that measured at the portal with such a small distance. The burning history and mass loss rate of a relative smaller pool fire inside the wind tunnel have been compared with that just at the portal. The measured results are convinced to be identical.

As for the flow speed range to be considered, the cross air flow should have an enough momentum to deflect the main body of the flame of the biggest pool fire in the experiments to reach the state of mainly attaching to the ground [20–22]. According to the work of Woods [21], this state is shown to be achieved when the inverse value of Richardson number

$$R_i = \left(1 - \frac{T_a}{T_f}\right)\frac{gL}{u^2} \tag{1}$$

reaches a value of about $R_i^{-1} = 7$ for the 20 cm square pool fire. This suggests a cross air flow speed of about 2.5 m/s correspondingly. So, the cross air flow is ranged in the experiments from 0 to 2.5 m/s with increment of about 0.5 m/s (It is observed in the experiments that a cross air flow with speed of about 1.5–2.0 m/s has already strong enough momentum to deflect the flame body to be mainly attaching to the ground).

Medium square pool fires in the transition flame flow regime are used as fire source, with dimensions of 10 cm, 15 cm, 20 cm and 25 cm, using ethanol and heptane as fuel. These two typical fuels produce representative flames with highly soot or little soot, which is very important in the flame radiation emission. These pools are made by 5 mm thick steel plate with inner depth of 3.0 cm. During the experiments, the fuel surface level is maintained at 2.6 cm above the inner bottom of the pool with a constant freeboard or lip height of 0.4 cm. A device is used to maintain the fuel layer depth during the burning period as also shown in Fig. 1, in which the fuel layer controlling method is similar to that of Rasbash et al. [26]. This fuel supply and surface level maintaining device consists of three fuel storages. The fuel in the top storage (#1) flows into the middle one (#2) by gravity force. The middle fuel storage is connected to the bottom of the pool fire through a pipe with inner diameter of 32 mm. The fuel surface layer in the middle fuel storage is maintained to be flush with that in the pool fire with